AD-A240 154

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1991	Reprint 1-1-90 - 12-31-90

4. TITLE AND SUBTITLE
Reprinted from RLE Progress Report No. 133

5. FUNDING NUMBERS
AFOSR 90-0200
PE - 61102F
2313/A9

6. AUTHOR(S)
Dr Nathaniel I Durlach

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 91 0712

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NL
Air Force Office of Scientific Research
Building 410
Bolling Air Force Base, DC 20332

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Work by Dr. Durlach and his collaborators is summarized here.

91-09730

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

91 8 AUG 1991

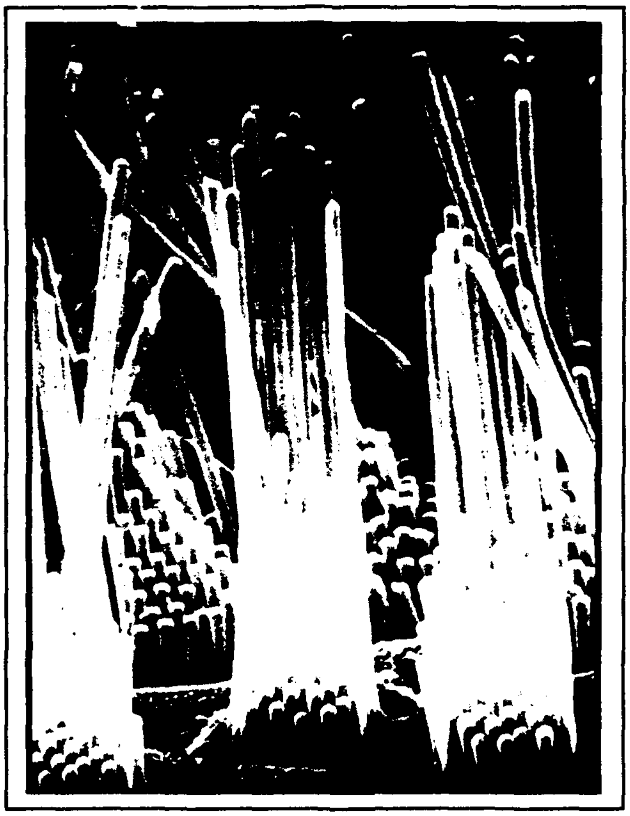
RLE Progress Report

No. 133

January 1 - December 31, 1990

Submitted by

Professor Jonathan Allen
Professor Daniel Kleppner



Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

RLE Progress Report No. 133

Cover and title page: In 1991, we celebrate two big anniversaries—the RadLab's 50th and RLE's 45th. The Research Laboratory of Electronics, which was established in 1946, grew out of MIT's wartime Radiation Laboratory (1940-45). In honor of the milestones that we are sharing this year, the cover of *RLE Progress Report No. 133* notes the rich tradition of communications research in RLE.

In the early days of RLE, former RadLab staff member Professor Jerome B. Wiesner, collaborating with Professors Yuk Wing Lee and Norbert Wiener, developed practical applications for the theory of nonlinear systems. By combining the methods and techniques of mathematicians and communication engineers, the study of communication theory in RLE was not confined to electrical systems.

As new theories of modern communication were introduced in the 1950s, they were applied to new studies of the nervous system. Professor Walter A. Rosenblith worked with Professor Norbert Wiener to apply statistical communication techniques to the field of communication biophysics. This research established quantitative relations between neuroelectric data and the characteristics of sensory stimuli.

This tradition continues today. For example, members of RLE's Auditory Physiology Group are studying the sound-induced motions of mechanically sensitive cells (hair cells) in the inner ear, which contain microscopic hairs that vibrate when the ear is stimulated by sound. These vibrations are transduced by the hair cells to excite nerve fibers that carry the information about the sound stimulus to the brain. Shown on the cover is a scanning electron micrograph of the microscopic sensory hairs of a lizard, prepared by Dr. Ruth Anne Eatock. Approximately 60 hairs project from each sensory receptor cell, and the receptor cells are organized by length (2 to 20 microns for the cells shown) in an orderly staircase array. The mechanical properties of these sensory hairs play an important role in determining the neural code for sound.

Dr. Eatock, a former postdoctoral fellow in RLE under the direction of Professor Thomas F. Weiss, is presently an Assistant Professor in the Physiology Department at the University of Rochester.

Our special thanks to the following staff members of the RLE Communications Group: Mary J. Ziegler for her exceptional editing, formatting, and scanning; Mary S. Greene for proofreading and preparation of the publications and personnel chapters; and Rita C. McKinnon for her help with proofreading. We also want to thank David W. Foss, Manager of the RLE Computer Facility, for his technical assistance.

We thank the faculty, staff, and students of RLE for their generous cooperation.

Editor:	Barbara Passero
Design and Illustration:	Robert H. Priest
Photography:	John F. Cook
Printer:	DS Graphics, Pepperell, Massachusetts
Typesetting:	This report was produced with IBM's BookMaster Software. Mylar negatives were printed on an IBM 4250-II electro-erosion printer.

ISSN 0163-9218

Chapter 1. Sensory Communication

Academic and Research Staff

Dr. Joan M. Besing, Professor Louis D. Braida, Lorraine A. Delhorne, Nathaniel I. Durlach, Dr. Donald K. Eddington, Dr. Kenneth W. Grant, Professor Richard M. Held, Dr. Xiao Dong Pang, Dr. William M. Rabinowitz, Dr. Christine M. Rankovic, Dr. Charlotte M. Reed, Dr. Mandayam A. Srinivasan, Timothy J. Stellmach, Dr. Rosalie M. Uchanski, Dr. Victor W. Zue, Dr. Patrick M. Zurek

Visiting Scientists and Research Affiliates

Dr. Richard L. Freyman, Dr. Janet D. Koehnke, Dr. Jack Kotik, Dr. Neil A. Macmillan, Dr. Karen L. Payton, Dr. Patrick M. Peterson, Dr. Bruce Schneider

Graduate Students

Santosh Ananthraman, Jyh-Shing Chen, Paul Duchnowski, Kiran Dandekar, Joseph A. Frisbie, Eric Fuchs, Julie E. Greenberg, Yoshiko Ito, Zoher Karu, Wolfgang G. Knecht, Gregory R. Martin, Matthew H. Power, Michael T. Richey, Barbara Shinn-Cunningham, Robert Stadler, Hong Z. Tan

Undergraduate Students

Michael Aponte, Susan E. Bach, Younes Borki, Swaroop Gantela, Andrew H. Grant, Darby A. Hailes, John Hedgcock, Mary Hou, Michael H. Lim, Manilo Lopez, Sandra Y. Ma, Quintin T. Ndibongo, Prashun Patel, Charles Reisman, Rebecca J. Renn, Alexander P. Rigopulos, Sumeet Sandhu, Lynore Taylor, Derrick Yim

Technical and Support Staff

Kai P. Chen, Ann K. Dix, Paula M. Ferguson, Seth M. Hall, Eleanora M. Luongo, Michael T. Tuyo

1.1 Introduction

The Sensory Communication Group is conducting research on (1) the auditory and tactual senses, (2) speech-reception aids (both auditory and tactual) for individuals who are hearing-impaired or deaf, and (3) human-machine interfaces for teleoperator and virtual-environment systems (involving the visual as well as the auditory and tactual senses). Within the domain of hearing aids, research is being conducted on systems that bypass the outer and middle ear and directly stimulate the auditory nerve electrically (cochlear prostheses), as well as on systems that stimulate the system acoustically. The research on taction is focused not only on speech reception for the totally deaf, but also on the ability of the human hand to sense and manipulate the environment. Within the domain of human-machine interfaces, topics of special interest concern the development of principles for mapping the human sensorimotor system into non-anthropomorphic slave mechanisms (or the equivalent in virtual space) and the ability of the human sensorimotor system to adapt to alterations of normal sensorimotor loops caused by the presence of the interface.

1.2 Hearing Aid Research

Sponsor

National Institutes of Health
Grant 5 R01 DC00117

Project Staff

Dr. Joan M. Besing, Professor Louis D. Braida, Lorraine A. Delhorne, Nathaniel I. Durlach, Dr. Kenneth W. Grant, Dr. Christine M. Rankovic, Dr. Charlotte M. Reed, Dr. Rosalie M. Uchanski, Dr. Victor W. Zue, Dr. Patrick M. Zurek

This research is directed toward the development of improved hearing aids for people suffering from hearing impairments that cannot be treated medically. Since the major problem for most people with impaired hearing is a degraded ability to understand speech, and since medical treatments are available for abnormalities of the outer and middle ear, the work is directed towards aids that better match speech signals to residual auditory function in people with impairments central to the middle ear. More specifically, the research is directed at improving speech reception for people with sensorineural impairments. The work performed during the past year can be divided into

four project areas: linear amplification, speech token variability, prediction of speech intelligibility, and aids to speechreading.

1.2.1 Linear Amplification

This research has focused on (1) theoretical analysis of suggested prescriptive methods for fitting frequency-gain characteristics to individual listeners, (2) investigation of the reduction in speech intelligibility associated with strong high frequency emphasis,[1] and (3) the use of adaptive frequency-gain characteristics to combat the effects of background interference on target speech intelligibility.[2] Current research on adaptive frequency-gain characteristics includes both experimental intelligibility studies to determine the potential benefits of adaptive systems and development of real-time signal-processing for implementing such systems.

1.2.2 Speech Token Variability

Performance in intelligibility tests for speech segments depends on the set of segments to be identified and the characteristics of the talker. It also depends, however, on the number and variability of the speech tokens chosen to represent a given segment. (The use of a single token for each segment leads to the use of artifacts as perceptual cues and results in artificially high performance.) In order to predict performance on such tests, it is necessary to model the effects of token variability. With this goal in mind, we are (1) measuring the physical variability of tokens,[3] (2) determining the perceptual effects of this variability on intelligibility for both normal and impaired listeners,[4] and (3) developing a model that relates the perceptual effects to the acoustic characteristics of the stimuli.

1.2.3 Prediction of Speech Intelligibility

This project involves the development of computational methods for predicting the intelligibility of speech subjected to a waveform degradation. Our work in this area during the past grant year has consisted of three components: (1) completion of preliminary experiments using a two-talker database (to determine the feasibility of our approach); (2) establishing the amount of speech data required for our base set of experiments (based on theoretical considerations for information transfer); and (3) completion of the first portion of these base experiments.

1.2.4 Aids to Speechreading

Our study of aids to speechreading has focused on (1) developing a theoretical understanding of the effects of speechreading supplements and (2) evaluating the training requirements involved in teaching Cornett's manual Cued Speech system to listeners with normal hearing. The theoretical work exploits two related models of speech segment confusions: a model that describes confusions in terms of a multidimensional Thurstonian decision model[5] and a model that specifies the relation between the decision space for multimodal (e.g., audiovisual) presentation conditions and the constituent unimodal spaces.[6] Our results on the training of Cued Speech reception suggest that the relatively small amount of training required to achieve high levels of performance on isolated speech segments is a poor indicator of training requirements for sentence reception.

---

1 C.M. Rankovic and P.M. Zurek, "Rollover with High-Frequency Emphasis," *J. Acoust. Soc. Am.* 87: S87 (1990).

2 C.M. Rankovic, R.L. Freyman, and P.M. Zurek, "Potential Benefits of Varying the Frequency-Gain Characteristic for Speech Reception in Noise," submitted to *J. Acoust. Soc. Am.*

3 L. Taylor, *Token Variability of Intra-Speaker Speech: Fricative Consonant Sounds.* S.B. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

4 K.M. Millier, *Intelligibility of Vowels Represented by Multiple Intra-Speaker Tokens,* S.B. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

5 L.D. Braida, "Development of a Model for Multidimensional Identification Experiments," *J. Acoust. Soc. Am.* 84: S142(A) 1988.

6 L.D. Braida, "Crossmodal Integration in the Identification of Consonant Segments," *Quart. J. Exper. Psych.*, forthcoming: L.D. Braida, "Two Types of Audiovisual Integration for the Identification of Speech Segments," *J. Acoust. Soc. Am.* 88: S82 (1990).

1.3 Multimicrophone Hearing Aids

Sponsor

National Institutes of Health
Grant 2 R01 DC00270

Project Staff

Nathaniel I. Durlach, Dr. Xiao Dong Pang, Dr. William M. Rabinowitz, Dr. Patrick M. Zurek

The long-term goal of this research is the development of sensory aids that improve the ability of hearing-impaired listeners to function in complex acoustic environments. The more immediate goal is to determine the benefits that can be achieved for monaural listening through the use of microphone arrays that sample the acoustic field at more than one point in space. Since the reception of speech is the most important problem for the hearing impaired, the target signal of primary interest is speech.

To enhance monaural speech reception, we envision a microphone array that resolves the incoming signals into simultaneous directional channels, followed by a coding operation that transforms these resolved signals in such a way that resolution is preserved at the perceptual level after the signals are summed for presentation to a single ear.[7] Such a system would permit the monaural listener (like the normal binaural listener) to monitor all directions simultaneously, to detect and localize in the same operation, and to focus on a single direction. Our initial work on the microphone array is directed toward the creation of a single directional channel containing the target signal (assumed to arise from a target source straight ahead of the listener) and the reduction of interference from sources directionally distinct from the target source. Parallel processing of array outputs to achieve simultaneous multiple directional channels will be considered only after further progress on the coding problem has been achieved.

During the past year, work has focused on acoustic measurements for fixed-array design, adaptive beamforming (analysis of an adaptive noise canceller and construction of a real-time system), and experimental studies of natural spatial coding.

1.3.1 Acoustic Measurements for Fixed-Array Design

We have completed measurements on a set of transfer functions from many source angles within the upper hemisphere to 10 microphone locations situated along the frame of eyeglasses worn by KEMAR wihin our anechoic chamber. Two arrays of particular interest are an array that encompasses much of the eyeglass span and a second one that is substantially smaller (a few cm span), situated either broadside along the eyeglass front or endfire along the temple. We have also begun to employ analytic formulations of diffraction and scattering for interpreting the acoustic data and for predicting the performance of optimum processors.

1.3.2 Adaptive Beamforming: Analysis of the Adaptive Noise Canceller

The adaptive beamforming algorithm that has been the focus of much of our work, the Griffiths-Jim beamformer,[8] can be viewed as a simple preprocessor operating in conjunction with an adaptive noise canceller (ANC), which was described by Widrow et al.[9] Two of the problems encountered with this beamforming system are associated with, and can be described more simply in terms of, the ANC. The first problem is known as misadjustment and is due to fluctuations in the adaptive filter's weights. The second problem comes from leakage of the target signal into the reference channel, which is ideally free of target for best estimation of the jammer. Both problems increase in severity with input target-to-jammer power ratio. Our previously-proposed modifications of the Griffiths-Jim beamformer were ad hoc attempts to address these problems.[10] In order to gain a more

[7] N.I. Durlach, R.C. Corbett, M.V. McConnell, W.M. Rabinowitz, P.M. Peterson, and P.M. Zurek, "Multimicrophone Monaural Hearing Aids," RESNA 10th Annual Conference, San Jose, California, 1987.

[8] L.J. Griffiths and C.W. Jim, "An Alternative Approach to Linearly Constrained Adaptive Beamforming," *IEEE Trans. Antennas Propag.* AP-30: 27-34 (1982).

[9] B. Widrow, J.R. Glover, Jr., J.M. McCool, J. Kaunitz, C.S. Williams, R.H. Hearn, J.R. Zeidler, E. Dong, Jr., and R.C. Goodlin, "Adaptive noise cancelling: Principles and Applications," *Proc. IEEE* 63: 1692-1716 (1975).

[10] J.E. Greenberg, *A Real-time Adaptive-beamforming Hearing Aid*, S.M. thesis, Dept. of Electr. Eng. and Comput.

complete understanding of the limitations of the ANC, we are now attempting to derive analytic expressions for system performance.

1.3.3 Adaptive Beamforming: A Head-Worn Real-Time System

We are continuing development of a battery-powered, body-worn audio processor based on a Motorola DSP56001 chip. Functionally, the unit accepts two microphone inputs and provides a single output. The hardware is general-purpose, and the device can be programmed to perform a wide variey of algorithms requiring one or two input signals. To date, it has been programmed to implement the modified Griffiths-Jim beamformer as well as a simple algorithm that automatically selects the microphone signal estimated to have less noise (due to head shadow).

1.3.4 Spatial Coding: Natural References

Our work on spatial coding[11] is aimed at developing transformations of multiple source signals (which we expect eventually to be able to extract with microphone arrays) to render these signals maximally intelligible when summed for monaural presentation. As background for this work we have measured the extent to which natural coding systems—monaural and binaural hearing—keep spatially-separate sources perceptually separate. Specifically, using two or three sources, we have measured the intelligibility of each source serving as the target in the presence of the others as interference. The results, averaged over source configurations, show an advantage of about 10 dB for binaural over monaural listening to two sources. As expected, this binaural advantage is reduced by introducing a second jammer.

1.4 Cochlear Prostheses

Sponsor

National Institutes of Health
Grant 1 P01 DC00361[12]

Project Staff

Professor Louis D. Braida, Lorraine A. Delhorne, Dr. Donald K. Eddington, Dr. William M. Rabinowitz, Dr. Charlotte M. Reed

The overall goal of this research project is to determine and understand the potential and limitations of cochlear prostheses and to develop improved prostheses. Residual sensorineural hearing is measured prior to implantation in connection with subject selection and to provide baseline data for later comparison. Following implantation, auditory performance is evaluated by studying psychophysical performance, discrimination of speech elements, and comprehension of speech and the acoustic environment. Attempts are made to identify and measure central processing abilities that are relevant to speech-reception performance with an implant and that may help explain the large intersubject variations observed. Also, for comparison purposes, speech-reception tests are performed using a promising multichannel tactile vocoder. To minimize differential learning effects in the comparison, these tests are restricted to discrimination of speech segments. Further research focuses on alternative speech-processing schemes to achieve improved implant performance. This research capitalizes on analytic results from other parts of our research and the direct accessibility of the implanted electrode array (via a percutaneous plug). During the past year, work has focused on evaluation of overall performance, the effects of background noise, and alternative speech processing.

1.4.1 Overall Performance

This work is concerned with documenting implantees' speech-reception abilities at a variety of different levels and establishing relationships among different tests. At present, about twenty subjects have participated in our program and about eight have completed most of our routine evaluations. Some preliminary observations which

Sci., MIT, 1989; J.E. Greenberg, P.M. Zurek, and P.M. Peterson, "Reducing the Effects of Target Misalignment in an Adaptive Beamformer for Hearing Aids," *J. Acoust. Soc. Amer.* 85: S26 (1989).

[11] C.R.Corbett, *Filtering Competing Messages to Enhance Mutual Intelligibility,* S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1986.

[12] Subcontract from Massachusetts Eye and Ear Infirmary. Dr. Joseph B. Nadel, M.D., Principal Investigator.

appear interesting are the following: Auditory word recognition with the IEEE/Harvard sentences correlates highly with auditory performance on the NU-6 monosyllabic word test (R = 0.98). Speech-segment discrimination tests reveal some subjects with relatively good performance who (on the basis of other tests) derive little communicative benefit from their implant; these subjects may be particularly good candidates for specialized aural rehabilitation. Finally, measures of speech-segment identification performance, in contrast to discrimination performance, relate directly to overall measures of communicative benefit.

1.4.2 Effects of Background Noise

Everyday communication often occurs in the presence of background noise. During this past year we began studies on the effects of background noise on speech reception with the Richards (Symbion) implant system. In comparison to normal-hearing subjects tested under the same conditions, the implantees appear about 15 dB more sensitive to noise for both consonant and vowel identification. Analyses are presently underway to examine the dependencies of particular consonant and vowel features on speech-to-noise ratios.

1.4.3 Alternative Speech and Processing

Collaboration with Blake Wilson and his associates at the Research Triangle Institute (RTI) has continued. Best perceptual results have been obtained with a "supersampler" scheme consisting of interleaved-pulse stimulation that is updated over the six channels at a rate of 1600 Hz. Substantial improvements over previous results (obtained with the normal processor which employs simultaneous multichannel stimulation) have been demonstrated for both monosyllabic word recognition and sentence reception.[13]

1.5 Binaural Hearing

Sponsor

National Institutes of Health
Grant 2 R01 DC00100[14]

Project Staff

Nathaniel I. Durlach, Dr. Patrick M. Zurek

The long-term goal of this program is (1) to develop an integrated, quantitative theory of binaural interaction that is consistent with psychophysical and physiological data on normal and impaired auditory systems and (2) to apply our results to the diagnosis and treatment of hearing impairments.

Research in this area (performed under a subcontract from Boston University) has focused on lateralization phenomena. One series of studies has explored the effect of onset cues for long-duration sounds. It has been found that the degree to which onset information dominates lateralization depends not only on the strength and consistency of the lateralization information in the ongoing stimulus, but also on the extent to which the ongoing stimulus appears to constitute a single "auditory object." Thus, for example, the onset's control of lateralization can be greatly reduced by introducing into the continuing signal an abrupt change in amplitude (an increase as well as a decrease).

Work on the precedence effect with pairs of binaural noise bursts has shown that there is a large variation in the strength of the effect across noise tokens (some tokens even show a reverse precedence effect). Efforts are now being made to determine the stimulus variables (such as phase spectrum, cross-spectral magnitude, etc.) that are responsible for these phenomena.

We have also completed an analysis of the probability distributions of interaural cues in simple binaural detection stimuli.[15] This report presents derivations of these distributions in calculable form, as well as a summary of the dependence of variance on signal-to-noise ratio.

[13] B.S. Wilson, C.C. Finley, D.T. Lawson, R.D. Wolford, D.K. Eddington, and W.M. Rabinowitz, "New Levels of Speech Recognition with Cochlear Implants," *Nature*, forthcoming.

[14] Subcontract from Boston University. Professor H. Steven Colburn, Principal Investigator.

[15] P.M. Zurek, "Probability Distributions of Interaural Phase and Level Differences in Binaural Detection Stimuli," submitted to *J. Acoust. Soc. Am.*

1.6 Clinical Applications of Binaural Hearing

Sponsor

National Institutes of Health
Grant FV00428 [16]

Project Staff

Dr. Patrick M. Zurek

Work on clinical applications of binaural hearing has focused on comparisons between the performance of listeners with sensorineural impairments and listeners with normal hearing on tests of binaural detection, localization, and contralateral masking. The results show, as expected, that impairments often lead to reduced performance in these tests, and that performance is correlated across tests. However, correlation between performance on these tests and audiometric configuration is relatively weak; unexplained intersubject variance remains disturbingly large.

1.7 Tactile Communication of Speech

Sponsor

National Institutes of Health
Grant 5 R01 DC00126

Project Staff

Lorraine A. Delhorne, Nathaniel I. Durlach, Dr. William M. Rabinowitz, Dr. Charlotte M. Reed, Dr. Mandayam A. Srinivasan

Previous research on (1) tactual communication of speech among the deaf-blind in which the tactual stimulation is achieved by direct physical contact with the speaker and (2) tactual aids that transform acoustic signals into patterns of tactual stimulation and thus function at a distance has led us to the following conclusions: (1) The tactual sense is capable of receiving continuous speech at nearly normal speaking rates with nearly zero error rates; (2) Subjects are capable of integrating a relatively impoverished tactual signal with visual speechreading to achieve essentially normal speech-reception performance; (3) Limitations on the speech-reception performance obtained with current tactual aids are due primarily to inadequacies in the design of the aids and/or in the training received with these aids; and (4) There are no fundamental scientific obstacles to eliminating these inadequacies and achieving much improved speech reception for a wide range of patients. Conclusions (1) and (2) are based on (a) extrapolations of results obtained with relatively crude experimental devices on subjects with relatively limited training;[17] (b) tactual communication performance exhibited by the deaf-blind using direct-contact methods;[18] and (c) preliminary results on the ability of individuals who are experienced in the visual reception of Cued Speech to integrate visual speechreading with direct-contact tactual cueing. Conclusions (3) and (4) are essentially corollaries of conclusions (1) and (2).

With the above research as background, our ultimate general goal can be stated simply as follows: To develop schemes for processing acoustic signals and displaying these processed signals to the tactual sense so that, when accompanied by equivalent training, they provide speech-reception performance comparable to that demonstrated for the direct-contact methods. Discussion of our progress during the past year is divided into the following subsections: (a) Basic study of encoding and display schemes, (b) Tactual supplements to speechreading, (c) Evaluation of practical aids, and (d) Completion of work on natural methods of

---

[16] Subcontract from University of Connecticut. Dr. Janet D. Koehnke, Principal Investigator.

[17] N.I. Durlach, C.E. Sherrick, and J.D. Miller, "Sensory Substitution: Visual and Tactual Methods," chapter in *Speech Communication Aids for the Hearing Impaired: Current Status and Needed Research,* Report of CHABA Working Group 95 by C.S. Watson, R.A. Dobie, N.I. Durlach, H. Levitt, J.D. Miller, C.E. Sherrick, F.B. Simmons, G.A. Studebaker, R.S. Tyler, and G.P. Widin, forthcoming; C.M. Reed, N.I. Durlach, and L.D. Braida, "Research on Tactile Communication of Speech: A Review," *ASHA Monograph Number 20,* 1982; C.E. Sherrick, "Basic and Applied Research on Tactile Aids for Deaf People: Progress and Prospects," *J. Acoust. Soc. Am.* 75: 1325-1342 (1984).

[18] C.M. Reed, W.M. Rabinowitz, N.I. Durlach, L.D. Braida, S. Conway-Fithian, and M.C. Schultz, "Research on the Tadoma Method of Speech Communication," *J. Acoust. Soc. Am.* 77: 247-257 (1985).

tactual communication. Recent reports of our work are available in Reed et al.;[19] and Tan et al.[20]

1.7.1 Basic Study of Encoding and Display Schemes

Previous research on transmitting information through the tactual (i.e., cutaneous, proprioceptive, kinesthetic) sense has been confined almost exclusively to stimulation of the skin; manipulation of joint angles (i.e., hand postures) has been essentially ignored. Research is now underway to determine information transfer rates achieved by manipulation of joint angles, as well as by both joint angle manipulation and cutaneous stimulation combined. New devices to drive the hand are being developed and preliminary discrimination and identification experiments are being performed. One issue of particular interest concerns the extent to which subjects highly experienced in outputting via manual manipulation (such as typists and pianists) are exceptionally good at learning to receiving information manually.

1.7.2 Tactual Supplements to Speechreading

Research in this area over the past year has been concerned with comparing the effectiveness of a simple, low-bandwidth supplement to speechreading presented auditorally versus tactually. The signal consisted of a 200-Hz tone modulated by the envelope of an octave band of speech centered at 500 Hz. The resulting signal was used to drive a high-performance single-channel vibrator for tactile stimulation or Koss earphones for auditory stimulation. Preliminary results indicate a consistent improvement in speechreading using the single-channel vibrator; however, this benefit is small compared to that obtained with the auditory supplement. Various hypotheses concerning the observed difference in performance between the tactile and auditory supplements are now being examined.

1.7.3 Evaluation of Practical Aids

Experiments are being conducted to compare segmental resolution through a wearable tactile device (the seven-channel Tactaid VII which uses zero-crossing analysis to track the first two speech formants) and a laboratory version of the Queen's University tactile aid (a nine-channel device which operates using a traditional vocoder principle). Results currently available indicate roughly similar performance through the two devices. An initial evaluation of a profoundly hearing-impaired adult (who had worn a Tactaid VII for approximately two months prior to testing) indicate substantial benefits to speechreading for segments but only modest benefits for sentence materials. During the coming year, we plan to re-test this subject as well as to provide Tactaid VII devices to additional subjects who will participate in periodic evaluations.

1.7.4 Completion of Work on Natural Methods of Tactual Communication

During the past year, we have continued work on our detailed statistical analysis of measurements of speech produced by Tadoma users (in Tadoma, speech is understood by using the hand to sense the mechanical actions of the face associated with speech production); data collection and analysis for a study of the visual reception of sign language as a function of presentation rate to serve as a reference for previous results on the tactual reception of sign language; and further studies of the tactual reception of Cued Speech in conjunction with both speechreading and Tadoma.

---

[19] C.M. Reed, N.I. Durlach, L.D. Braida, and M.C. Schultz, "Analytic Study of the Tadoma Method: Effects of Hand Position on Segmental Speech Perception," *J. Speech Hear. Res.* 32: 921-929 (1989); C.M. Reed, N.I. Durlach, L.A. Delhorne, W.M. Rabinowitz, and K.W. Grant, "Research on Tactual Communication of Speech: Idea, Issues, and Findings," *Volta Rev.* 91: 65-78 (1989); Also in *Research on the Use of Sensory Aids for Hearing-Impaired People*, ed. N.S. McGarr; C.M. Reed, L.A. Delhorne, N.I. Durlach, and S.D. Fischer, "A Study of the Tactual and Visual Reception of Fingerspelling," *J. Speech Hear. Res.* 33: 786-797 (1990); C.M. Reed, W.M. Rabinowitz, N.I. Durlach, L.A. Delhorne, L.D. Braida, J.C. Pemberton, B.D. Mulcahey, and D.L. Washington, "Analytic Study of the Tadoma Method: Improving Performance through the Use of Supplementary Tactual Displays," submitted to *J. Speech Hear. Res.*; C.M. Reed, N.I. Durlach, and L.A. Delhorne, "Natural Methods of Tactual Communication," chapter in *Tactile Aids for the Hearing Impaired*, ed. Ian R. Summers (New York: Taylor and Francis Ltd., forthcoming).

[20] H.Z. Tan, W.M. Rabinowitz, and N.I. Durlach, "Analysis of a Synthetic Tadoma System as a Multidimensional Tactile Display," *J. Acoust. Soc. Am.* 86: 981-988 (1989).

1.8 Super Auditory Localization for Improved Human-Machine Interfaces

Sponsor

U.S. Air Force - Office of Scientific Research
Grant AFOSR 90-200

Project Staff

Nathaniel I. Durlach, Dr. Richard M. Held, Dr. Xiao Dong Pang, Dr. William M. Rabinowitz, Dr. Patrick M. Zurek

The normal human auditory system suffers from a number of deficiencies in its ability to localize sound sources. The auditory system determines the distance or elevation of a source poorly, is substantially worse at detecting changes in azimuth when the source is off to the side than when it is in front or back, and occasionally makes front-back confusions when the head is motionless. However, when localization is considered in the context of human-machine interfaces such as those employed in teleoperator or virtual-environment systems, there is an opportunity to recode source location in a manner that improves localization. In other words, one can transform the acoustical cues available to the listener for determing source location (i.e., alter the manner in which source location is represented in the binaural acoustic stimulus) in such a way that the listener achieves super localization.

The principal research questions in attempting to achieve super localization concern the ability of the human operator to adapt to such transformations and to switch back and forth between the normal cue system and the altered cue system *rapidly* and *reliably*. Although certain consequences of these transformations can be predicted theoretically from our models of normal human audition, those involving perceptual learning and adaptation cannot be predicted. A major goal of the research is to determine, understand, and model the perceptual effects of these transformations.

The planned research involves the study of adaptation to a wide range of transformations using a specially designed virtual-environment system for presenting the transformed localization cues, a variety of training procedures to achieve adaptation, and localization tests to measure adaptation that include detection and localization in multiple-source environments and dynamic tests of localization constancy, as well as discrimination and identification of single sources. To the extent that reliable and reversible adaptation can be demonstrated, the results of this research will provide important new options for improved interface design. Further background in this area can be found in Durlach.[21]

During the past year, our efforts have been directed primarily towards the development of appropriate facilities for this work.

Our desire to incorporate reverberation into head-related transfer functions (HRTFs) for virtual auditory displays has resulted in some suggested changes in the Convolvotron, a key device for creating virtual auditory environments. Numerous discussions between our staff and the manufacturer of the Convolvotron have lead to an outline for improvement of the filter length, memory size, computational method, speed, and data structure of the system. Also, at our request, the manufacturer has developed a new software package for making HRTF measurements in a reverberant environment using the Convolvotron. The modified system is currently under evaluation in our laboratory.

In order to be able to measure HRTFs for individual listeners, a computer-controlled speaker placement system is being constructed with a speaker mounted on an 8-ft. diameter ring which can be driven in two degrees of freedom for placing the speaker anywhere on the surface of a sphere whose center coincides with the center of subjects's head. The mechanical structure of the system has been completed, including the ring, the platform, the motors, the driving mechanism, and the sensing mechanism for motor control. A master's thesis has been outlined to implement the remaining control mechanisms, measure HRTFs, incorporate the HRTFs into the Convolvotron, and conduct and analyze the relevant experiments.

A mechanical head-tracker with six degrees of freedom has been designed and is under construction in the laboratory. The purpose of this tracking device is to overcome three major problems with the currently available (Polhemus) tracker: restricted work space, time delay, and electromagnetic interference. The mechanical tracker will provide a much larger operating range than the Polhemus tracker (9-ft. radius as opposed to 2-ft.), will be essentially immune to electromagnetic interference. and will have delays

[21] N.I. Durlach, "Auditory Localization in Teleoperator and Virtual-Environment Systems: Ideas, Issues, and Problems," *Percept.*, forthcoming.

less than 100 microseconds (from a 25 kHz A/D convertor). The construction of the mechanical head-tracker and its interface with a PC are expected to be completed within the next few months.

A complete software system for conducting localization and adaptation experiments has been developed. This system includes a menu-driven user interface for entering and displaying experimental parameters, and a "controller" for calibrating spatial coordinate systems, controlling stimulus presentations (both probabilistically and temporally), and prompting, recording, storing, and organizing subject responses. The initial transformations implemented include rotation of the interaural axis, expansion and contraction of the interaural axis, and exponentiation of HRTFs.[22] A computer-controlled visual display is available in the form of spatially distributed light bulbs. In addition to conventional keyboard control, manual control of sound source location has been made available through the use of a Power Glove. Preliminary observations suggest that the use of these non-auditory inputs improves externalization of virtual acoustic targets.

A DEC 5000 work station with a graphics engine has been purchased and a graduate student has begun to develop software for generating 3-D visual stimuli for a head-mounted visual display (to be integrated with the auditory display).

A preliminary analysis has been made of algorithms for achieving interaural expansion. The algorithms considered are those of Durlach and Pang[22] and Van Veen and Jenison.[23] The second set, unlike the first, are linear. Thus, they should be superior in multiple jammer environments (to the extent that the approximations are acceptable). For virtual auditory environments, however, where the experimenter has separate control of individual sound sources, issues other than linearity dominate.

1.9 Research on Reduced-Capability Human Hands

Sponsor

U.S. Navy - Office of Naval Research
Grant N00014-90-J-1935

Project Staff

Lorraine A. Delhorne, Nathaniel I. Durlach, Dr. Xiao Dong Pang, Dr. Mandayam A. Srinivasan

The general objectives of our research on hand function are to increase basic knowledge of manual sensing and manipulation, aid in the design and evaluation of artificial hands for robotic and teleoperator systems, and improve clinical diagnosis and treatment of hand impairments. Reports of some of our previous work in this general area are available in Durlach et al.[24] and Pang et al.[25]

The particular research being conducted in this grant focuses on the ability of the human hand to sense and manipulate the environment under various types of constraints. Such constrained hand performance is being studied in connection with hand-design questions in the area of teleoperator systems. Determination of how performance degrades as various capabilities of the normal human hand are eliminated provides important background for hand-design decisions. The constraints to be studied are imposed by experimental gloves and local anesthetics, as well as by various types of hand impairments (resulting from injuries, birth defects, or diseases).

Efforts in the first area have involved (1) interaction with clinics to establish a flow of patients with appropriately impaired hands, (2) study of techniques for constructing experimental gloves that reduce tactile sensitivity in a controllable manner, and (3) selection and acquisition of materials for constructing various types of splints for limiting movement and force output of the hand. The technique for glove construction that appears most promising involves the dipping of latex finger cots in plastic coating material.

[22] N.I. Durlach and X.D. Pang, "Interaural Magnification," *J. Acoust. Soc. Am.* 80: 1849-1850 (1986).

[23] B. Van Veen and R. Jenison, "Auditory Space Expansion via Linear Filtering," *J. Acoust. Soc. Am.*, forthcoming.

[24] N.I. Durlach, L.A. Delhorne, A. Wong, W.Y. Ko, W.M. Rabinowitz, and J.M. Hollerbach, "Manual Discrimination and Identification of Length by the Finger-Span Method," *Percept. Psychophys.* 46(1): 29-38 (1989).

[25] X.D. Pang, H.Z. Tan, and N.I. Durlach, "Manual Discrimination of Force Using Active Finger Motion," *Percept. Psychophys.*, forthcoming.

Efforts in the second area have involved (1) conceptual analysis of how various types of manual tasks/tests relate to various underlying sensimotor capabilities of the hand; (2) selection of specific tasks/ tests in the clinical domain, the elementary analytic domain, the general functional domain, and the teleoperator operational domain; and (3) development of facilities for performing these tasks/tests and for recording hand actions during the tasks/tests.

1.10 Skin Biomechanics

Sponsor

National Institutes of Health
Grant 5 R29 DC00625

Project Staff

Dr. Mandayam A. Srinivasan

Whenever we touch an object, the source of all tactile information is the spatio-temporal distribution of mechanical loads on the skin at the contact interface. The relationship between these loads and the resulting stresses and strains at the nerve terminals within the skin plays a fundamental role in the neural coding of tactile information. Although empirical determination of the stress or strain state of a mechanoreceptor is not possible at present, mechanistic models of the skin and subcutaneous tissues enable prediction and verification of peripheral neural response. The research under this grant is directed towards applying theoretical and computational mechanics to analyze the biomechanical aspects of touch—the mechanics of contact, the transmission of the mechanical signals through the skin, and their transduction into neural impulses by the mechanoreceptors.

1.10.1 Determination of Geometric and Material Properties of the Primate Fingertip

The first step in performing mechanistic analyses of the primate fingertip is to determine its geometric and material properties. We have indented the fingerpads of humans and monkeys in vivo using a line load delivered by a sharp wedge, and photographed the resulting skin surface deflections. We have shown that the homogeneous elastic model of the fingertip only roughly approximates the experimental data, while a simple alternative model, which views the fingertip as an elastic membrane filled with an incompressible fluid (like a "waterbed"), predicted the observed profiles very well.[26] We are planning more experiments to determine the external and internal geometry of the primate fingertip as well as its material properties.

1.10.2 Finite Element Analyses of Two-dimensional Models

We have performed finite element analysis on a series of mechanistic models of the fingerpad under a variety of mechanical stimuli. The models range from a semi-infinite medium to cylindrical distal phalanx, composed of either a homogeneous elastic material or a thick elastic shell containing a fluid. Simulations of the mechanistic aspects of neurophysiological experiments involving mapping of receptive fields with single point loads, determination of spatial resolution of two-point stimuli, and indentations by single bars as well as periodic and aperiodic gratings have been carried out. The results show, for example, that the strain energy density at the receptor site is a leading contender for the relevant stimulus that causes the responses recorded from slowly adapting afferent fibers. More generally, we have demonstrated the power of computational mechanics in investigating the relationship between tactile stimuli imposed on the skin and the resulting peripheral neural response. The analyses are being extended both in terms of the mechanical stimuli applied on the fingerpad as well as the geometrical and material properties of the fingertip.

1.10.3 Tactile Sensing of Shapes and Softness

We have been collaborating with Dr. LaMotte of Yale University School of Medicine in conducting psychophysical and neurophysiological studies of the encoding of shapes and degree of softness in mechanoreceptive afferents. Based on a theoretical analysis of the mechanics of contact, we have demonstrated that the receptors respond to the low-pass filtered versions of surface pressures.[27] Thus, curvature of the skin surface under an

---

[26] M.A. Srinivasan, "Surface Deflection of Primate Fingertip Under Line Load," *J. Biomech.* 22(4): 343-349 (1989).

[27] M.A. Srinivasan and R.H. LaMotte, "Encoding of Shape in the Responses of Cutaneous Mechanoreceptors," in *Information Processing in the Somatosensory System,* eds: O. Franzen and J. Westman, Wenner-Gren Interna-

object, which we know from differential geometry is approximated by the second spatial derivative of surface deflection, is coded without differentiating (which is a noise enhancing process), but by exploiting its relation to surface pressure. We will be using our finite element models to further explore the neural coding of shapes and softness.

1.10.4 Development of a Computational Theory of Touch

Although the "hardware" of the tactile apparatus in humans and robots is different, they have the common feature of mechanosensors embedded in a deformable medium. Thus the computational problem of coding (predicting sensor response for a given mechanical stimulus at the surface) and decoding (inferring the mechanical stimulus at the surface by suitably processing the sensor response) need similar mechanistic analyses for their solution. We have developed such a "computational theory" for an idealized medium subjected to arbitrary pressure or displacement loading conditions, and give explicit formulae for the coding and decoding problems.[28]

In collaboration with Dr. Annaswamy of the Department of Aerospace and Mechanical Engineering, Boston University, we have investigated some of the identification and control problems that occur in the context of manipulation, when compliance is present in the end-effectors as well as in the object.[29] In order to understand the fundamental aspects of these tasks, we have analyzed the problem of identification of compliant objects with a single finger contact, was well as under a two-finger grasp. Assuming that the finger and the compliant object are constrained to deform along a single spatial dimension, we have carried out parameter identification using either force or displacement inputs to the rigid backing of the end-effector. Based on this analysis, control strategies are developed to achieve a desired manipulation of the object in the workspace. Animated graphical renderings are being developed to visually illustrate the presence of absence of slipping and crushing during an active manipulation task. The theoretical results can be used to generate testable hypotheses for human or robot experiments on tactual sense.

1.11 Publications

Annaswamy, A.M., and M.A. Srinivasan. "Adaptive Control for Grasping and Manipulation of Compliant Objects with Compliant Fingerpads." Accepted for presentation at the American Control Conference, Boston, June 1991.

Annaswamy, A.M., and M.A. Srinivasan. "Manipulation of Compliant Objects with Compliant Fingerpads: Identification and Control Issues." *Proceedings of the IEEE Conference on Decision and Control,* Hawaii, December 1990.

Braida, L.D. "Crossmodal Integration in the Identification of Consonant Segments." *Quart. J. Exper. Psych.* (1991). Forthcoming.

Braida, L.D. "Two Types of Audiovisual Integration for the Identification of Speech Segments." *J. Acoust. Soc. Am.* 88: S82 (1990).

Delhorne, L.A., J.M. Besing, C.M., Reed, and N.I. Durlach. "Tactual Cued Speech as a Supplement to Speechreading." *ASHA* 32: 73 (1990).

Durlach, N.I. "Auditory Localization in Teleoperator and Virtual Environment Systems." *Percept.* Forthcoming.

Grant, K.W., L.D. Braida, and R.J. Renn. "Single-band Envelope Cues as an Aid to Speechreading." *Quart. J. Exper. Psych.* (1991). Forthcoming.

Grant, K.W., and L.D. Braida. "Evaluating the Articulation Index for Audiovisual Input." *J. Acoust. Soc. Am.* (1991). Forthcoming.

Koehnke, J., and P.M. Zurek. "Localization and Binaural Detection with Monaural and Binaural

tional Symposium Series (New York: Macmillan Press, 1990); M.A. Srinivasan and R.H. LaMotte, "Tactile Discrimination and Representation of Texture, Shape, and Softness," in *Human-Machine Interfaces for Teleoperators and Virtual Environments,* eds. N.I. Durlach, T. Sheridan, and S. Ellis, *NASA Report* (1990), forthcoming.

28 M.A. Srinivasan, "Tactile Sensing in Humans and Robots: Computational Theory and Algorithms," Newman Lab. Tech. Rep., Dept. of Mech. Eng., MIT, 1988.

29 A.M. Annaswamy and M.A. Srinivasan, "Manipulation of Compliant Objects with Compliant Fingerpads: Identification and Control Issues," *Proceedings of the IEEE Conference on Decision and Control,* Hawaii, December 1990; A.M. Annaswamy and M.A. Srinivasan, "Adaptive Control for Grasping and Manipulation of Compliant Objects with Compliant Fingerpads," accepted for presentation at the American Control Conference, Boston, June 1991.

Amplification." *J. Acoust. Soc. Am.* 88: S169 (1990).

LaMotte, R.H., and M.A. Srinivasan. "Surface Microgeometry: Neural encoding and Perception." In *Information Processing in the Somatosensory System.* Eds. O. Franzen and J. Westman. Wenner-Gren International Symposium Series. New York: Macmillan Press, 1990.

Pang, X.D., H.Z. Tan, and N.I. Durlach. "Manual Discrimination of Force Using Active Finger Motion." *Percept. Psychophys.* (1990). Forthcoming.

Peterson, P.M., S.-M. Wei, W.M. Rabinowitz, and P.M. Zurek. "Robustness of an Adaptive Beamforming Method for Hearing Aids." *Acta Otolaryngologica Suppl.* 469: 85-90 (1990).

Rankovic, C.M., R.L. Freyman, and P.M. Zurek. "Potential Benefits of Varying the Frequency-gain Characteristic for Speech Reception in Noise." Submitted to *J. Acoust. Soc. Am.*

Rankovic, C.M., and P.M. Zurek. "Rollover with High-frequency Emphasis." *J. Acoust. Soc. Am.* 87: S87 (1990).

Reed, C.M., L.A. Delhorne, N.I. Durlach, and S.D. Fischer. "A Study of the Tactual and Visual Reception of Fingerspelling." *J. Speech Hear. Res.* 33: 786-797 (1990).

Reed, C.M., N.I. Durlach, and L.A. Delhorne. "Natural Methods of Tactual Communication." In *Tactile Aids for the Hearing Impaired.* Ed. Ian R. Summers. New York: Taylor and Francis. Forthcoming.

Reed, C.M., M.H. Power, N.I. Durlach, L.D. Braida, K.K. Foss, J.A. Reid, and S.R. Dubois. "Development and Testing of Artificial Low-Frequency Speech Codes." *J. Rehab. Res. Dev.* 28 (1991). Forthcoming.

Srinivasan, M.A. "Tactual Interfaces: The Human Perceiver." In *Human-Machine Interfaces for Teleoperators and Virtual Environments. NASA Report.* Eds. N.I. Durlach, T. Sheridan, and S. Ellis. Washington, D.C.: NASA, 1990.

Srinivasan, M.A., and R.H. LaMotte. "Tactile Discrimination and Representation of Texture, Shape, and Softness." In *NASA Report.* Eds. N.I. Durlach, T. Sheridan, and S. Ellis. Washington, D.C.: NASA, 1990.

Srinivasan, M.A., J.M. Whitehouse, and R.H. LaMotte. "Tactile Detection of Slip: Surface Microgeometry and Peripheral Neural Codes." *J. Neurophys.* 63 (6): 1323-1332 (1990).

Srinivasan, M.A., and R.H. LaMotte. "Encoding of Shape in the Responses of Cutaneous Mechanoreceptors." In *Information Processing in the Somatosensory System.* Eds. O. Franzen and J. Westman. Wenner-Gren International Symposium Series. New York: Macmillan Press, 1990.

Wilson, B.S., C.C. Finley, D.T. Lawson, R.D. Wolford, D.K. Eddington, and W.M. Rabinowitz. "New Levels of Speech Recognition with Cochlear Implants." *Nature.* Forthcoming.

Zurek, P.M., J.E. Greenberg, and P.M. Peterson. "Sensitivity to Design Parameters in an Adaptive-beamforming Hearing Aid." *Proc. ICASSP '90,* pp. 1129-1132.

Zurek, P.M., and C.M. Rankovic. "Potential Benefits of Varying the Frequency-gain Characteristic for Speech Reception in Noise." *J. Acoust. Soc. Am.* 87: S87 (1990).

Theses

Ito, Y. *Auditory Discrimination of Power Spectra for Roving Two-Tone Stimuli.* Ph.D. diss. Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

Millier, K.M. *Intelligibility of Vowels Represented by Multiple Intra-speaker Tokens.* S.B. thesis. Dept. of Elect. Eng. and Comput. Sci., MIT, 1990.

Taylor, L. *Token Variability of Intra-speaker Speech: Fricative Consonant Sounds.* S.B. thesis. Dept. of Electr. Eng. and Comput. Sci. MIT, 1990.

Wang, L. *Two Talker Activity Labelling by Humans.* S.B. thesis. Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.